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EXAMINING THE MENTAL MODEL CONVERGENCE PROCESS AND ITS CONSEQUENCES

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14. ABSTRACT
This project demonstrates the impact of mental model convergence on team performance. Results suggest that teams achieve better performance when they converge on goals, then on the approach to complete their task, and finally on how they will allocate work. These types of findings can inform training materials. Computational models developed were used to determine optimal communication patterns and run simulated experiments. Findings suggest that teams perform close to optimal when they achieve mental model convergence first and then shift to taskwork. These types of results inform the design of future human experimentation. Results were transitioned to other ONR-funded PIs and to submarine domain.

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ABSTRACT

The purpose of this research project is to understand how the mental model convergence process unfolds over time, as well as how team processes and performance are impacted by the mental model convergence process and the shared mental models resulting from it. When this research effort began in 2002, minimal empirical research captured shared mental models. The number of empirical studies has increased since that time, but most of these studies capture shared mental models at distinct points in time *after* team interaction. Much of our research focuses at capturing the mental model convergence process as it occurs *during* team interaction. The limitation of this approach is that we assume team cognition is captured through the use of surrogate measures such as team communication.

The metrics and analytical approaches developed and applied through my research project demonstrate the role of mental model convergence and shared mental models on a team's ability to perform. For example, teams achieve better performance when they converge on their goals, then on the approach they will use to complete their task, and finally on the way they will allocate their work. This result was found in two studies using different samples and methods (i.e., similarity assessments of sentence stem completion tests and survival analysis of convergence points in team communication). Our results also suggest when in their life cycle teams begin to integrate various types of information. Specifically, they integrate information about the parameters governing their task and the approach they intend to use during the second quartile of their existence. These types of findings are transitionable by incorporating them into training and/or facilitator materials.

We have also developed computational models of team processes. For instance, our model of team communication has been used to determine the optimal communication pattern and to run simulated experiments. Our findings suggest that teams perform close to optimal when they do not initiate any work on their task until half way through their life cycle. During the first half of their life cycle, they should discuss mental model content (i.e., the parameters governing their task, the approach they will use to complete the task, and how they will allocate work among themselves). These types of results can inform the design of future human experimentation, thereby ensuring that the monies are spent in the most effective manner possible.

The results of this project have been transitioned to other ONR-funded PIs, where my measurement techniques have been applied to other tasks. Additionally, I worked with colleagues from NAVAIR and the University of Tennessee to transition our findings to the submarine domain through the TRAnsitioning CKI findINGS (TRACKING) project funded by Capable Manpower Future Naval Capabilities. Finally, my expertise in team cognition, developed through this project, was applied to an NSA/OSD-funded project aimed at creating a tool to facilitate the agile development of graphical concepts of operations.

OBJECTIVES

This section summarizes this project's objectives and approach taken to address those objectives.

[1] Objective: understand the mental model convergence process when teams work under various conditions (e.g., time pressure, environmental uncertainty)

Approach: analyze extant de-identified data collected at the University of Massachusetts Amherst during my previous ONR-funded research projects

[2] Objective: examine the impact of converged mental models on team processes and outcomes when teams work under various conditions (e.g., time pressure, environmental uncertainty)

Approach: analyze extant de-identified data collected at the University of Massachusetts Amherst during my previous ONR-funded research projects

DATA COLLECTION

(NOTE: This section is repeated from the Final Report Written for ONR N000140610031; the grant under which much of the data was collected)

Two-hundred sixteen undergraduate business students from the University of Massachusetts Isenberg School of Management were randomly formed into teams of three. The students received extra credit for their participation. Additionally, the teams with the highest performance received a cash bonus of $50 per team member (odds of winning were approximately 1:5).

The participants performed a personnel scheduling task adapted from Bachrach et al. (2001), Earley (1994), and Steele-Johnson et al. (2000). The participants were asked to assign 10 employees, each with different hourly wages to a work schedule for a hypothetical organization. Workforce requirements (i.e., number of employees per shift) were given to the team. To ensure collaboration, each team member represented a different organizational function with conflicting rules for schedule completion, in the sense that maximizing one function's rules led to breaking the others' rules. The functional roles and associated rules were: (1) human resources representative, each employee can work no more than 10 hours per day and 50 hours per week; (2) union representative, each employee must work four hours per day if called into work and 30 hours per week; (3) operations manager, the schedule requirements must be met exactly. If any of the rules were broken in the final schedule, a penalty was assessed. The task was pretested using a comparable sample to ensure that the students found the exercise interesting and that the level of difficulty was appropriate to the population and time allotted for each session.

We used a 2 (communication medium) x 2 (session) x 3 (condition) design. Three-person teams were randomly assigned to a computer-mediated (CM) or face-to-face (FF) ***communication medium*** to complete the simulated task. The FF team members were seated around a table in a private room. Each participant had a worksheet and instructions. Only one solution per team was accepted. The sessions were video-recorded; each participant gave consent to the video-recording procedure. A digital timer placed on the table recorded the time elapsed. The CM sessions were conducted in a laboratory consisting of 10 personal computers linked in a local area network. Thus, three teams could be simultaneously completing the behavioral simulation. Participants from one team were seated so no members from the same team were next to each other. Using this arrangement, the team members could see each other (since they were located in the same room), but were far enough apart to be unable to read each other's notes. Participants were not allowed to talk during the simulation. The teams in the CM condition communicated through a synchronous computer conferencing system specifically developed for the purposes of the simulation. The system consisted of a screen with the task requirements (this view was identical to the paper copy given to all participants in both media conditions), a text messaging area, and a timer depicting the elapsed time since the beginning of the session. A unique simulation environment was created for each team that allowed them to work synchronously on the schedule. All team members had equal access to the screen and could assign/delete workers, view any assignments or deletions made by team mates, and exchange messages with team mates. The communication was not anonymous; the messages were identified by the sender's name and appeared in the order in which they were sent. The team members could scroll through the communication history when/if they wanted to review past messages.

Each team completed two ***sessions***. The second session was scheduled at the convenience of all team members, between three and seven days after the first. The functional roles the team members represented, and their associated rules, remained the same for the first and second sessions, but the schedule requirements changed. In the first session, employee requirements per *day* were given (see Figure 1). For the second task, employee requirements per *shift* were given (see Figure 2), which made the second task more complex than the first.

Figure 1. Session 1 workforce schedule worksheet

WORKFORCE SCHEDULE WORKSHEET SCENARIO 1 Team ______							
Hour	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
8 – 10 am							
10 – 12 am							
12 – 2 pm							
2 – 4 pm							
4 – 6 pm							
6 – 8 pm							
Employees required per shift	3	3	5	4	6	7	4

Figure 2. Session 2 workforce schedule worksheet

WORKFORCE SCHEDULE WORKSHEET SCENARIO 2	Team ______						
Hour	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
8 – 10 am	2	2	3	2	4	4	4
10 – 12 am	2	2	3	2	4	4	4
12 – 2 pm	3	3	4	3	4	5	4
2 – 4 pm	3	3	4	3	4	5	4
4 – 6 pm	3	3	5	4	6	7	5
6 – 8 pm	3	3	5	4	6	7	5

The ***conditions*** were unrestricted, time pressure, and environmental uncertainty. Teams assigned to the unrestricted condition were given unlimited time to complete the task and were unbothered throughout the session. Under time pressure, teams were given 45 and 30 minutes to complete the task during the first and second sessions, respectively. Environmental uncertainty was introduced approximately 20 minutes into the session by promoting (first session) or demoting (second session) one employee. Sample sizes by condition are shown in Table 1.

Table 1. Behavioral simulation sample size by communication medium and condition

	FF	CM
Unrestricted	36	36
Time Pressure	30	31
Environmental Uncertainty	33	33

After study participants volunteered for the simulation, they were randomly assigned to teams. The teams were informed about the exact time when their team was scheduled. Upon arrival, the team members were introduced and seated. The teams were informed that the general goal of the simulation was to investigate how teams work together and reminded that the best performing teams would receive a prize of $50 for each team member. The teams were told that the task was estimated to take about 45 minutes to complete, but the quality of their work schedule determined the team's performance. The teams were not pressed to finish within 45 minutes and were left to work until all three members were satisfied with the solution (except in the time pressure condition). In the CM condition, a brief training session on the use of the computer software was conducted immediately after the instructions were given.

The teams read written instructions about the task before they started working together. After the task was completed and the final solution submitted to the experimenter, each participant individually completed a questionnaire regarding the team and its processes. Existing scales were used when available and were created for this study when no appropriate scale could be identified. The measures included collective efficacy (Riggs et al., 1994), goal acceptance (Latham & Steele, 1983), team membership (based on Ganster & Dwyer, 1995), work allocation (devised for this study), decision making (Coopman, 2001), team member skills (devised for this study), interdependence (Johnson et al., 1983), goal clarity (Weber & Weber, 2001), satisfaction (Van Dyne & LePine, 1998), cooperation (Campion et al., 1993), conflict (Jehn & Mannix, 2001), coordination (Denison et al., 1996), and cohesion (modified from Seashore, 1954).

Two dependent measures were used to assess team performance following the guidance of Straus and McGrath (1994), who identified quantity, quality and speed as the primary indicators of team task performance. In this experiment the teams were asked to develop one workforce schedule, in approximately 45 minutes. Thus, the quantity was not a relevant performance indicator in this study. The teams developed as many "practice" schedules as they wished, but were required to agree upon one final schedule per team for submission at the end of the simulation session. The teams' schedules were assessed for quality. Quality was calculated as the ***cost*** associated with the particular assignment developed, including penalties for any broken rules. Specifically, using each employee's cost per hour and the corresponding number of hours assigned to work, the cost per employee was calculated. The cost for all employees was added. Next, the schedules were checked to see if the rules given to the teams were enforced. Each time a rule was broken, a penalty of 1.8 times the respective employee wage was added. Finally, speed to solution was recorded as the ***time*** from the moment the team members started working until the final solution was submitted.

Our measurement approach created performance measures where better performance was the smaller value. To aid interpretation of results and follow the more conventional approach of "more is better," we transformed both measures. Cost performance reported is calculated as the optimal assignment score divided by a team's score. Thus, the closer a team's score is to the optimal score, the closer their cost performance is to 1.0 (i.e., higher values represent better cost performance). Time performance is calculated as the slowest team's time plus one minus a team's recorded time. Thus, the slowest team (i.e., the team with the worst time performance) has a score of 1 and the fastest team will have the highest score (i.e., the most minutes finished before the slowest team).

The face-to-face sessions were transcribed and the computer-mediated chat logs were captured. The raw transcripts from the face-to-face sessions were reviewed by a second person to verify completeness. Two researchers unfamiliar with the study hypotheses coded each message in the transcripts as one of seven topics. The inter-rate agreement was high, 87%-99%. The topics are:

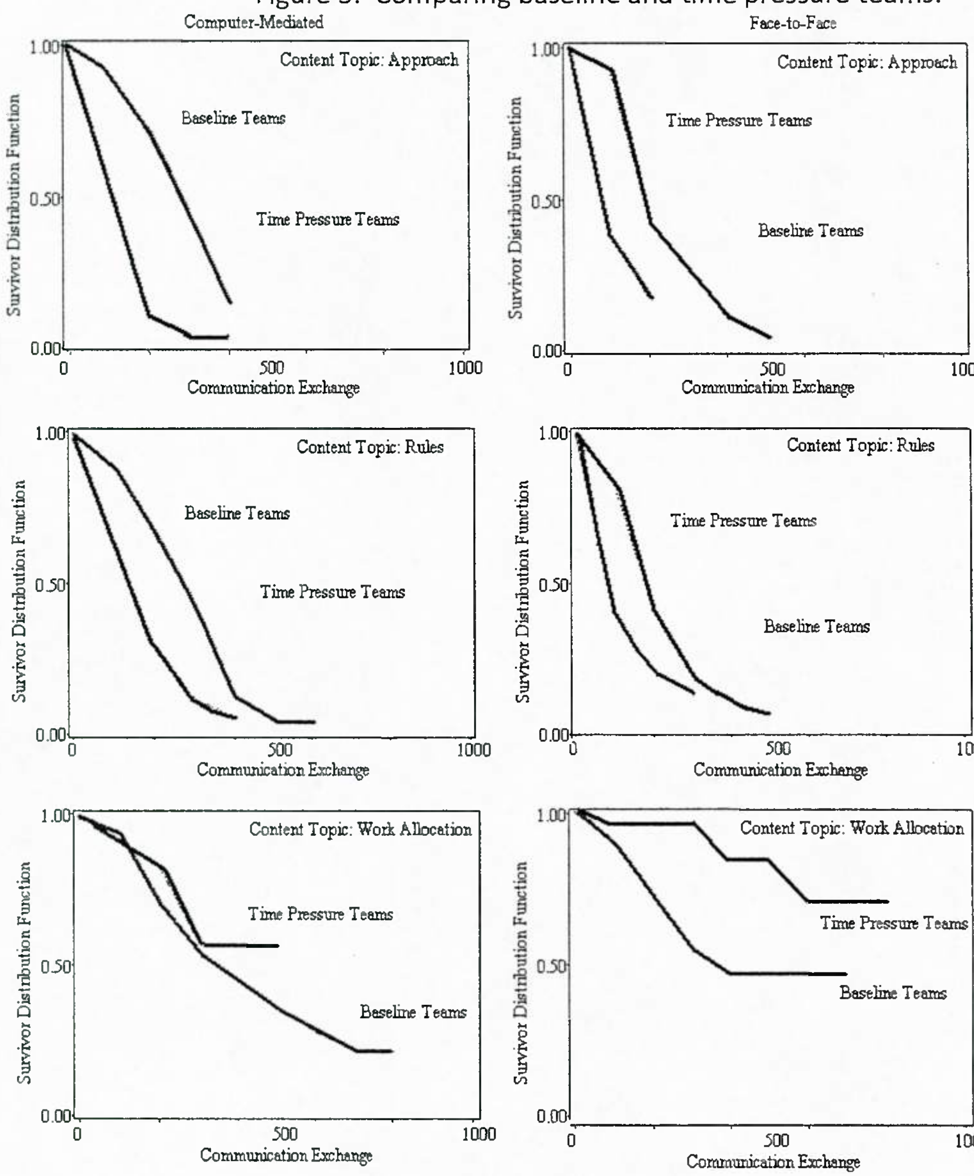
APPROACH	statement about how the team plans to attack the task *Examples:* (1) maybe I'll do mine on paper; (2) do we want to choose who will work on what days?
GOAL	statement about the objective of the assigned task (i.e., achieve the lowest cost to earn the extra credit)
MEMBER	statement about participant skills that may or may not be related to the task *Example:* I'm no good at math
RULES	statement about roles (i.e., union representative, hr manager, production manager), rules associated with each role (e.g., cannot work less than 4 hours per day or 30 hours per week), penalties associated with breaking rules, schedule requirements (e.g., day 1 requires 3 people) *Examples:* (1) no time limit or anything?; (2) no at least 30 hours per week
TASK	statement about assigning workers on the schedule, counting hours, etc. where the team members are actually doing the work (vs. discussing how they are going to do it)
WALL	WALL = Work Allocation statement about how the team members plan to distribute the tasks among themselves *Examples*: (1) so are we splitting the people or the days; (2) I will take days 1, 2, and 3; (3) I'll assign the workers while you calculate the hours
UNRELATED	statements unrelated to the task; these statements were removed for analysis *Examples:* (1) what are you doing tonight?; (2) how are the Red Sox doing?

Accomplishments

We have had many significant accomplishments toward our objectives during this 18 month project. First, we collaborated with the University of Connecticut to develop a broader set of tools to examine team communication. Specifically, we applied Markov Modeling approaches at different levels of abstraction to identify the combination of modeling and abstraction that best fit the existing data. We found that Markov Chain modeling with three topics (i.e., task, rules, and other) provided the best prediction of team performance. The most significant outcome of this research is that we devised a method for ascertaining the level of abstraction necessary. For this project, we reduced the number of data categories needed from 42 to 3. This type of reduction has implications for practice. If only three data categories are necessary for predicting team performance, the time required to collect and code the data can be significantly reduced. A manuscript is currently in preparation reporting these results.

Second, we expanded our analyses beyond the data collected from baseline teams to examine the communication processes of teams facing time-pressure and disruption. We applied event history analysis to the team communication strings to compare baseline and time pressure teams (see Figure 3). We found that computer-mediated teams converge more quickly on approach and rules mental model content when faced with time pressure than do the teams in the baseline condition. Conversely, face-to-face teams facing time pressure converged later than the teams in the baseline condition. In the disruption condition, teams reconverged on rules and approach content. Additionally, reconverged on approach content was more likely after the team had reconverged on their rules mental model. Finally, team achieved better performance by reconverging on approach content quickly after new information is received (i.e., they are disrupted). These findings have been presented at conferences. A manuscript is currently in preparation reporting these results.

Figure 3. Comparing baseline and time pressure teams.

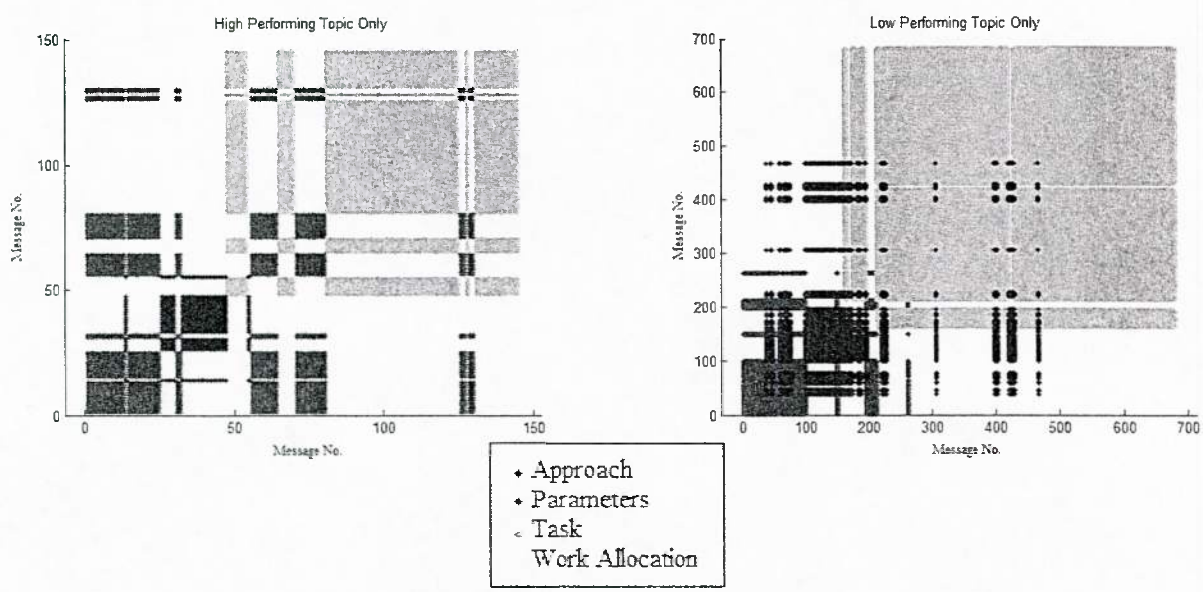


Third, we tested the relationship between personality characteristics and performance allowing for mixed operationalizations (i.e., average, variance, maximum, or minimum) of measures and for the possibility of nonlinear relationships. Our analysis shows that the best model to predict performance uses a mixture of operationalization approaches and nonlinear terms. The implications include:

- No one approach to assessing characteristics is enough. Moreover, across working conditions the approaches for using characteristics in the best model differed. Indeed, every type of operationalization (i.e., average, variance, maximum, minimum) was used in at least one model.
- More characteristics had significant curvilinear relationships with performance in the interruption and time pressure condition than for baseline conditions. As such, the more complex the working condition, the more complicated may be the relationships between characteristics and performance.
- While in the baseline condition the curvilinear relationships were U-shaped suggesting that values at the extremes were beneficial, in the interruption and time pressure condition, more relationships were inverted U-shaped suggesting that too much or too little of a particular characteristic hindered team performance. More research is needed to examine the nuances of these curvilinear relationships.

Finally, we began incorporating the exchange type into our analysis of communication strings. We found that high and low performing teams do not exchange significantly different types of information over time. In other words, the number of task-suggest or rules-information exchanges are not significantly different across teams. We, therefore, posit that the differences in performance may be attributable to the pattern of communication. Our preliminary results using recurrence plots to examine communication patterns visually suggests that high performing teams may have more concentrated exchanges on one exchange type whereas low performing teams may move among exchange types (see Figure 4). These findings have been presented at the INGroup 2013 conference and a manuscript is in preparation.

Figure 4. Recurrence Plots



In addition to addressing the objectives of this project, I completed a transition effort in collaboration with Norm Warner and Edward Lorek of NAVIAR, Joan Rentsch from the University of Tennessee, and Abhijit Deshmukh from Purdue University, which is funded by the Capable Manpower Future Naval Capability program at ONR. The objectives of this project were designed to directly support the requirements of the ONR Capable Manpower program. The project objectives are *threefold*: (1) provide technical expertise in the areas of human performance assessment, measurement methods, metrics definitions and data collection procedures along with providing an understanding of the theories of human decision making, teamwork, knowledge transfer and building, situational awareness and team mental model development; (2) conduct empirical validation of teamwork measures and methods using Advanced Pre-Deployment Training (APDT) scenarios and CASEX simulations; and (3) develop a Capable Manpower Roadmap for automated / electronic human performance measurement. These objectives have been met and the final report has been submitted.

Publications and Presentations

In addition to the aforementioned accomplishments, collaborations within the CKM/CDM program, and transition effort via Capable Manpower, multiple archival publications and presentations were completed.

Archival Publications in Journals and Edited Volumes

- McComb, S.A., Schroeder, A., Kennedy, D. & Vozdolska, R., 2012, "The Five Ws of Team Communication," *Industrial Management*, 54(5): 10-13.
- McComb, S.A. & Kennedy, D.M., 2011, "Facilitating Effective Mental Model Convergence: The Interplay among the Team's Task, Mental Model Content, Communication Flow, and Media," in Salas, E. et al., (Eds.), *Theories of Team Cognition: Cross-Disciplinary Perspectives*. New York: Routledge, 549-568.
- Hayne, S.C., Troup, L.J., & McComb, S.A., 2011, "'Where's Farah?': Knowledge Silos and Information Fusion by Distributed Collaborating Teams," *Information Systems Frontiers*, 13(1): 89-100.

Archival Publications in Conference Proceedings

- Lavetti, E. & McComb, S.A. "Examination of Cognitive Dynamics in a Complex Collaborative Context," Industrial and Systems Engineering Research Conference, Orlando, May 20-22, 2012.
- Schroeder, A., McComb, S.A., & Vozdolska, R., "Examining Teams as Dynamic Social Systems," Industrial and Systems Engineering Research Conference, Orlando, May 20-22, 2012. Paper selected as one of five Best Paper finalists for the Engineering Management track.

Conference Papers

- Kennedy, D.M. & McComb, S.A., "Composing the Ideal Team: An Algorithmic Study of Personality Characteristics and Team Performance," INGRoup Conference, Chicago, IL, July 12-14, 2012.

Conference Presentations

- Schroeder, A., Kennedy, D.M., & McComb, S. A., "Optimization in Project Team Staffing Decisions: Meeting Performance Expectations when Staffing One or Many Teams," INFORMS, Phoenix, October 14-17, 2012.
- Kennedy, D.M. & McComb, S.A., "Composing the ideal team: An algorithmic study of personality characteristics and team performance," INGRoup Conference, Chicago, IL, July 12-14, 2012.
- McComb, S.A., Vozdolska, R.P., & Kennedy, D.M., "Examining Team Communication Using Questionnaires, Simulation, and Optimization," 25nd European Conference on Operational Research, Vilnius, July 8-11, 2012.
- McComb, S.A., "Examining Similarities and Differences in the Mental Model Convergence Process Across Varying Conditions," Society for Industrial & Organizational Psychology Annual Meeting, San Diego, CA, April 28, 2012.
- Kennedy, D.M., McComb, S.A., & Balakrishna, P.V., "A Decision Support Tool for Team Staffing Decisions," INFORMS, Charlotte, NC, November 13-16, 2011.
- McComb, S.A., "Capturing the Mental Model Convergence Process through Team Communication," Society for Industrial & Organizational Psychology Annual Meeting, Chicago, IL, April 16, 2011.

Invited Presentations

- "Using Simulation to Examine Team Communication and Cognition," Purdue University, Krannert School of Management, Organizational Behavior Brown Bag Lunch Series, May 11, 2012.
- "Using Simulation and Optimization to Examine Team Cognition," Department of Defense, Human Factors Engineering Technical Advisory Group, May 1, 2012.
- "Using Simulation to Examine Team Communication and Cognition," Michigan State University Organizational Psychology Colloquium, September 30, 2011.